Design of 3-D Geometrical Model Using Point Clouds to aid Computational Analysis and Predict Deformation Rate in Process Plants

SHORT SYNOPSIS

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by

Dhritiman Mukherjee

21/Ph.D./044

Under the supervision of

Dr. Parul Gandhi

Professor, School of Computer Applications

Department of Computer Applications

School of Computer Applications

Manav Rachna International Institute of Research & Studies Sector-43, Surajkund–Delhi Road, Faridabad– 121004

SCHOOL OF COMPUTER APPLICATIONS

Certificate

I hereby declare that the Short Synopsis titled "Design of 3-D Geometrical Model Using Point Clouds to aid Computational Analysis and Predict Deformation Rate in Process Plants" being submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in the Department of Computer Applications under School of Computer Applications of Manav Rachna International Institute of Research & Studies, Faridabad during the academic year 2024-25. It is a bona fide record of original work carried out under the supervision of Dr. Parul Gandhi and has not been submitted in full or part to any other university or institute for a degree or diploma. Further, it is certified that Short Synopsis is plagiarism free and proof has been submitted.

Dhritiman Mukherjee
21/Ph.D./044

Signature of the Supervisor

Dr. Parul Gandhi,

Professor, School of Computer Applications

(Chairperson, DRC)

(Dean, School of Computer Applications)

Abstract

These Industrial Plants which run 24X7 & 365 days a year, which are also called Process Plants, where unplanned shutdowns are a major problem, is our main area of concern. These Process Plants include Petrochemical Plants, Refineries, Power Plants etc. With the aging of these plants, the role of inspection and maintenance are becoming increasingly vital. Inspection in these process plants is a semi-automated, manual-intensive task that relies on data extracted from instruments used by inspection engineers to evaluate the health of the assets. Visual inspection is completely dependent on the skill and intellect of the person performing it. For the enhancement of inspection technology, computational analysis is required to assess and replace the skill of the engineer by mathematical analysis which in turn require accurate and stable geometry. In the process of creation of a Geometry, 3D point clouds can play a major role nowadays, though there are some constraints of this technology. This research is focused on increasing the advancement of 3D point clouds technology and providing a more precise geometry. There are numerous good scanners available in the market, but the processing of point clouds from hardware to software is not good enough. Less interchangeability and data handling are the major barriers for expansion of this technology. If 3D point clouds data can be sourced from more robust and low-maintenance hardware, it is possible to improve accuracy through better algorithms. First, a scanner that provides high-quality point clouds from a robust, low-maintenance camera must be selected. Then, an algorithm must be used to stitch together the point clouds captured by the camera and enhance the point clouds' quality. The resulting point clouds will be used to create 3D Geometrical models and serve as input for mathematical models used in design and inspection processes in process plants.

Keywords: 3D Point Clouds, Fitness for Service, Inspection, Maintenance, Process Plants, Scanners, Camera, Geometrical Model

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1. Description Of Broad Area

The unplanned shutdowns are a major problem in the process plants and inspection is the only mode of prevention in the process plants. The objective is to automate the inspection and is focused on three areas: real-time digital inspection without the need of humans, smooth processing of 3D point clouds, and 3D point clouds scope identification. The research will figure out ways to expand the usage of 3D point clouds in inspection, maintenance, and real-time analytical models. The goal is to give innovative inspection methods to decrease technical glitch, and the challenge of 3D point clouds data processing. In the present situation laser technology is sensitive, maintenance intensive and costly.

The goal is to create a reasonably accurate geometry on which the following analysis can be performed.

- Predict Deformation
- Temperature Sensing
- Data Storage (Heuristics and API 579)

The main components of the 3D point Clouds: Instrument (Camera/Laser Scanner), Image Processing (Stitching pictures from various viewports) and Image Enablement/Enhancement (Running algorithms to estimate the profile of the object).

1 “Instrument” is referred as the device which captures the image as raster image as coordinates with metadata in terms of position and color and devices include 3D camera or Laser cameras which gives us geometry in terms of global coordinates.

2 “Image Processing” is the central work here which ends up stitching various pictures taken from different angles and coming up with a 3D geometry of the object. The challenge is to get the same or satisfactory quality of the object without too much dependency on Instrument. The overall processing if done with precise approximation will result in a better 3D Model which can serve the purpose.

3 “Image Enablement/Enhancement” directs the image enhancement to approximate the shape of the object from Mathematical algorithms without putting significant emphasis on quality of

the point clouds. The intent is to create more robust algorithms which can enhance the quality of the image to extract more point clouds which facilitates a precise 3D model.

1.1 Architecture of 3D Point Clouds

The architecture of the 3D points is a set of points that have 3 dimensional coordinates. There are devices which capture the image as raster image as coordinates with metadata in terms of position and color and devices, which include 3D Camera or Laser Camera, and these give us geometry in terms of global coordinates. The point clouds help in providing the outline geometry of many components and in certain cases, there can be the complete geometry of the body. This enables us to run mathematical models for analytics and create drawings of the same which will be more accurate. Our first intent is to create a reliable point cloud from a camera so that the challenges imposed by the terrestrial laser can be countered. The hardware for this should be robust and should not take frequent calibration. The output from these cameras can not only create 3D point clouds but also images which can be used to further enhance the quality of the 3D point clouds. A database of these geometries (derived from the point clouds) can be compared between different time stamps to create a rate of change of deformation and can help in predicting deformations.

1.2 Image Processing

The image processing component of the research is aimed at providing global coordinates to the point clouds generated by each of the cameras. The intent will be to position cameras at various different angles with predefined coordinates so that the pictures taken by the camera will also have a definite coordinate. Using markers as common points between pictures taken by different cameras, run an algorithm to stitch all the pictures together based on these common points, with the primary aim of translating the coordinates to the global coordinate system. This process will create a detailed point cloud which will have accurate coordinates for all the points.

1.3 Image Enablement

The image enablement theory, in this context, revolves around the concept of baseline

geometries and an algorithm that compares the baseline geometry with the geometry extracted from the cameras after image enablement. This will help us to quickly process the raw data and enable the point cloud to be rapidly converted into standard geometries, even if the image quality is not highly accurate. The main concept behind enabling these images is enhancing them with qualities derived from the standard models for quicker processing. The list of enablers needs to be identified to help segregate models that can be enhanced or enabled for further use.

2. Literature Review

According to the research conducted by Faig [1] discussed the details of the mathematical formulations proposed by Faig provides a foundation to calibrate systems effectively. It establishes fundamental principles linking processes to mathematical models and thus enables precise adjustment of cameras and sensors for reliable measurements and detailed 3D reconstruction [1]. This paper creates the base of how imaging is mathematically linked. This foundational work ensures that imaging systems can consistently and accurately capture spatial information from photographs or sensor data.

Zhu et al [2] established a method for calibrating cameras using video footage obtained in traffic scenarios. Camera calibration is essential for ensuring accurate measurements and reconstructions from video data. The paper talks about the dependency of environment for photogrammetry. It discusses challenges such as varying lighting, vehicle motion and scene complexity which highlights the need for robust calibration methods to enhance the reliability of measurements and reconstructions from video data.

Hanan et al [3] focused on utilizing close-range photogrammetric techniques for capturing detailed and accurate three-dimensional representations of cultural artifacts or structures associated with the Batak Toba culture. The paper provides a base to trap intricate features in a photogrammetric technique. It contributes to broader efforts in heritage conservation by offering non-invasive methods for comprehensive 3D modeling and archival purposes.

Several studies conducted by authors [4] focused on the application of multi-view Convolutional Neural Networks (CNNs) for the task of 3D shape recognition of three-dimensional shapes

through the utilization of multiple views and convolutional neural network architectures. It focuses on leveraging multiple viewpoints to enhance the accuracy of deep learning models in recognizing and classifying 3D shapes. It aids at creating the base for multiple perspectives of positioning the camera.

Mur-Artal et. al. [5] emphasized a monocular Simultaneous Localization and Mapping (SLAM) system. The primary focus is likely on presenting a robust and flexible solution for real-time SLAM using a single camera. The paper provides concept for accurate localization and mapping in dynamic environments.

In their study on camera and simulation [6], the authors talked about using 6DOF on Event Camera and using Simultaneous Location and Mapping (SLAM) which offers ideas for real-time 3D reconstruction [6]. Potentially revolutionize applications in robotics, and autonomous navigation. This study also showed that use of Event Camera may be a possibility for 3D point cloud reconstruction.

Rebecq et. al. [7] presented an algorithm that portrays capabilities of event cameras in effectively utilizing rapid camera movements and reconstruct a partially dense 3D representation of the surroundings. The paper introduces Evo, a geometric method for real-time parallel tracking and mapping and also has an algorithm which provides an understanding of how to register the images.

Riegler et. al. [8] discussed the limitations of existing methods in handling high-resolution 3D data and proposed OctNet as a solution. OctNet likely involves a representation of 3D data using an octree structure, a hierarchical data structure that adapts to the varying resolutions of different regions in the 3D space. This hierarchical representation could allow for more efficient processing and learning of 3D data, especially at higher resolutions.

Souto et. al. [9] demonstrated the methodology for extracting and processing 3D edge-points from RGB-D sensor data, as well as the algorithms or techniques employed for stairs and doors recognition. The goals are likely to improve the robustness and efficiency of mobile robot

localization by incorporating these natural landmarks. The paper provides an idea about Object identification, which is relevant to this paper.

Chen et. al. [10] talked about developing a comprehensive learning framework that directly translates volumes of data into 3D point cloud. It talks about an end-to-end approach for learning to generate 3D point cloud by translating volumes between different representations. Evaluation metrics can be used to assess the performance of the generated 3D point cloud. The efficiency of generating detailed 3D point cloud can be improved directly from input data.

Tools such as the fusion of LIDAR and Camera [11] for multi-View 3D Object Detection Network designed for autonomous driving. This network focuses on accurately detecting and localizing objects from multiple viewpoints to improve the ability of autonomous vehicles to understand their surroundings.

This paper talks about an unsupervised learning approach for jointly estimating distance from monocular videos [12], without the need for ground truth depth or pose information. This paper provides methods to use monocular depths estimation and challenges. It also addresses challenges such as handling various lighting conditions and improving accuracy in depth estimation for virtual environments.

Tools such as Bundle Fusion as a real-time 3D reconstruction method can achieve globally consistent reconstructions by dynamically integrating surface information while continuously tracking and fusing depth maps from multiple views [13]. This paper provides a good understanding of the surfacing capabilities by demonstrating how this method will achieve real-time and globally consistent 3D reconstruction.

Fan et. al. [14] address the challenge of 3D object reconstruction from 2D images and proposes the PSGN as a solution. This neural network is probably designed to create 3D points representing the geometry of an object based on the information presented in a single input image. The findings include evaluating PSGN (Point Set Generation Network) in this paper. It also evaluates PSGN's effectiveness in generating accurate and detailed 3D models directly from 2D images and

highlights its potential for advancing 3D object reconstruction.

The strengths and limitations of different point cloud generation techniques, addressing their applicability to Visual SLAM systems, was discussed by Zhang et. al. [15]. It highlights key challenges in the field and potential areas for improvement in terms of accuracy, efficiency, and robustness. Some applications including SLAM and Virtualization is evaluated. SLAM, which stands for Simultaneous Localization and Mapping uses 3D point clouds to create real-time maps and locations within them and this aids in navigation for robots and autonomous vehicles. Virtualization employs these 3D point clouds and builds detailed digital replicas of physical objects and environment, essential for other simulations.

Huang et.al.[16] outline the key challenges and opportunities associated with applying deep learning to point clouds, discussing the strengths and limitations of existing methods. The findings include evaluating the opportunities to apply deep learning methods. This survey covers some applications such as 3D object classification, segmentation and detection, and highlights the advantages and disadvantages of each approach, which is why it is relevant to this paper.

Yu et. al. [17] introduced an architecture that improves the ability of deep neural networks to capture contextual information at different scales, contributing to advancements in image analysis and understanding. The findings include the use of Deep Neural Networks on 3D point cloud. It introduces a new architecture for deep neural networks that improves the ability to capture detailed spatial information in images.

Zhou et. al. [18] uses the same event camera as SLAM (Simultaneous Localization and Mapping) and adds a new approach that enhances the accuracy of the estimation and increases the density of the reconstruction. This involves the implementation of a new probabilistic depth-fusion strategy. This approach also improves performance for cameras in various environments compared to traditional stereo methods. The solution to the uncertainty of the estimation can be understood from this paper.

Liang et. al. [19] talked about a 3D object detector capable of utilizing both LIDAR and cameras

to achieve highly precise localization. The design utilizes continuous convolutions to merge image and LIDAR feature maps at various resolution levels. This is one of my base papers which provides a reason to look into fuse images without using LIDAR.

Choy et. al. [20] utilize the field of computer vision by providing a unified framework for 3D object reconstruction, addressing the challenges associated with varying viewpoints and improving the robustness and accuracy of the reconstruction process.

In this study the authors [21] presented experimental results and evaluations that aim at demonstrating the effectiveness of the proposed approach in predicting accurate depth information from videos captured by unknown cameras in real-world scenarios. It presents a method to learn depth, camera motion, object motion and camera settings from single-camera videos, which is relevant to this paper. It also helps in understanding the gaps in the non-standard cameras.

The authors in this study presented experimental results and evaluations that are likely geared towards demonstrating the effectiveness and accuracy of DEEPVCP in comparison to existing point cloud registration methods. This research contributes to the advancement of techniques for aligning 3D point clouds through the application of end-to-end deep learning approaches. The findings include new technology of DEEPVCP application to our research.

Numerous researchers [23] presented experimental results and evaluations that demonstrate the performance and effectiveness of RealPoint3D in generating realistic and accurate 3D reconstructions from single images. The research contributes to the field of computer vision, particularly in the area of 3D object reconstruction, offering a novel and efficient solution to this challenging problem. The paper helps in understanding the RealPoint3D on reconstruction.

The study proposed by Bryner et.al. [24] proposed a method to track the posture of an event camera 6-DOF in a known environment using a photometric 3D map (i.e., intensity plus depth information) built via classic dense 3D reconstruction algorithms. The method in this paper leverages the high-speed and high dynamic range of event cameras to improve performance in

more dynamic environments. Geometry manipulation and the reconstruction algorithm are very implementable in this paper.

The study by the authors [25] introduced PointFlowNet, a model designed for learning representations in the context of 3D point cloud tasks, including generation, reconstruction, and classification. It identifies 3D shapes from point clouds using machine learning. It helps computers understand and work with 3D data more effectively. It is relevant to this paper as this paper helps in understanding Generation, Reconstruction and Classification in response to 3D point clouds.

An approach discussed in [26] for 3D reconstruction using an event camera, has a large dynamic range and a sensor with much reduced power, latency, and data cost. While most recent event-based 3D reconstruction techniques depend on stereo vision, this study used a monocular event camera to reconstruct the problem into multi-view geometry from silhouette. It identifies the problems of Stereo vision and ways to eradicate the same.

Xia et. al. [27] used an approach that emphasized the use of deep transfer learning techniques. This approach involves transferring knowledge learned from one domain to another, enhancing the model's ability to diagnose faults in machinery with limited labeled data. The findings are the use of Deep Transfer Learning Technique, which is where a computer model requires training in one activity in order to be applied to another similar task.

Xia et. al. [28] talked about using Neural Networks on Point clouds. It describes a new way to predict energy use and production of renewable energy using a type of computer model called a GRU-RNN (Gated Recurrent Unit – Recurrent Neural Networks). The model in this paper looks at past data to make future predictions more accurate. The findings include understanding Neural Networks on Point Clouds and how to manage energy better in smart grids, which are used in modern electricity networks.

Chen et. al. [29] presented tools that integrate three parts: image cropping, image retrieval and point cloud reconstruction. It finds similar images with known 3D models in a database, retrieves

these models and then adjusts them to match the original 2D image.

Zhao et. al. [30] talked about the technical aspects of their approach, explaining how binocular stereo vision is used to capture depth information, and how 5G technology enhances the speed and efficiency of data transfer in the context of virtual reality-based face modeling. The findings of this paper are how Binocular stereo vision can be used for depth information.

Patel et. al. [31] developed an innovative iterative method for 3D multi-angle point cloud stitching that combined the k-nearest neighbors (kNN) with an Iterative Closest Point (ICP) algorithm. Using this combined methodology, it is simple to compute the necessary transformation to merge point clouds into a single model. This method focuses on minimizing the error between surrounding point clouds. This paper is helpful in understanding the effectiveness of the algorithm for use.

Surmen, H. K. [32] reconstructed items included 24 distinct shapes and were made of metal, cloth, plastic, glass, wood, ceramic, and organic textures. A thorough analysis of the textured and solid models created from the objects was done. It investigated the effects of item geometry, texture properties, photo angle, and distance in addition to looking for solutions to problems with variables affecting the accuracy and mesh quality of the 3D models.

Xu, et. al. [33] described the current approaches lack uniformity due to diverse data sources and scene complexities. Recent developments in deep learning and computer vision yield encouraging results when it comes to aligning unregistered point clouds; nonetheless, assessments frequently depend on small datasets and ignore photogrammetric 3D mapping scenarios. This work reviews state-of-the-art registration techniques in detail and evaluates how well they work with various point clouds data types. The analysis, which focuses on feature-based coarse registration and dense fine registration via cloud-to-cloud optimization, identifies the advantages, difficulties, and potential directions of both techniques. Over 10 approaches have been tested, and most of the algorithms have success rates less than 40%, suggesting that there is still potential for improvement, particularly when it comes to handling complex geometry and occlusions and sparse correspondence search. The study's conclusion outlines future research directions and suggests the

most effective approaches for each registration phase.

Choi et. al. [34] suggested a method to estimate the faces of the mesh within a specified tolerance ϵ while capturing all of its geometric characteristics. This is done by using a toroidal patch-based spatial data structure. This facilitates determining the camera position and gaze route, enabling the key characteristics of the mesh to be captured.

An affordable substitute for LiDAR-based systems is multi-camera 3D perception, which is becoming more and more common in autonomous driving applications [35]. Nevertheless, current algorithms frequently ignore temporal and geographical relationships between camera systems. In response, the creator created UniScene, a multi-camera unified pre-training framework that reconstructs 3D scenes and optimizes models for certain purposes. UniScene efficiently performs pre-training on unlabeled image-LiDAR pairings by leveraging occupancy as a representation. UniScene outperforms monocular approaches and achieves a 25% reduction in 3D training annotation costs, indicating promising outcomes for the practical use of autonomous driving.

3. Research Gaps

1. The research gap identified in this context lies in the semi-automated manual process or highly maintenance intensive digital process to extract Point Clouds which are not cost-effective and need human intervention to calibrate.
2. To enhance inspection technology, there's a need for computational analysis to supplement or replace human judgement with mathematical analysis, necessitating accurate and stable geometric data. 3D point clouds offer a promising avenue for creating such geometry, but there are constraints to be addressed.
3. Current limitations of 3D point cloud technology, particularly in the accuracy and seamless integration of point cloud data. Existing methods often fall short in leveraging advanced hardware and state-of-the-art algorithms to effectively enhance and stitch point clouds, resulting in less precise geometric models.
4. Despite advancements, there remains a need for more automated approaches that prioritize geometrical data and computational analysis to achieve higher precision and objectivity in inspection processes.

4.Problem Statement

Inspection in these process plants is a semi-automated, manual-intensive task that relies on data extracted from instruments used by inspection engineers to evaluate the health of the assets. Various high-tech instruments are used, but the decision to use them is primarily guided by visual inspection which is dependent on the skill and intellect of the person performing it. For the enhancement of inspection technology, computational analysis is required to assess and replace the skill of the engineer by mathematical analysis which in turn require accurate and stable Geometry.

In the process of creation of a Geometry, 3D point clouds can play a major role nowadays, though there are some constraints of this technology. This research is focused on increasing the advancement of 3D point cloud technology and providing more precise geometry by the use of Robust Hardware and using state-of-the-art algorithms which can enhance and stitch the point clouds to have an accurate Geometrical model. The results of the analysis will pre-empt the engineers to know about problems in advance and also have historical data to run various mathematical functions.

5. Research Objectives

1. To identify an appropriate method for obtaining point clouds from a robust and low-maintenance camera.
2. Identify an algorithm to stitch together the point clouds captured by the camera.
3. Apply Image enhancement techniques to improve the extraction of high-quality point clouds.
4. Create and validate 3D Geometrical models using resulting point clouds.
5. Analyze the proposed 3D Geometrical model to predict rate of deformation at an early stage.

6. Research Methodology

The main research plan revolves around the quality of the point cloud from the laser. The aim is to match this quality or even compensate for lower quality data by improving the variance through various mathematical models applied to the acquired data. The Laser Scanners which is or will be used majorly from companies like Far (https://www.faro.com/en/Products/Hardware/Focus-Laser-Scanners), Leica (https://leica-geosystems.com/en-in/products/laser-scanners) and

Surphaser (https://www.surphaser.com/). These companies are mostly working on LIDAR technology, which stands from Light Detection and Ranging Technology.

LIDAR measures distances using laser pulses that emit infrared light. The sensor calculates the distances from the scanner and sends the coordinates back to the application after measuring the amount of time it took for the light to reflect back to it after these pulses have reflected back. The gathered point clouds are datasets that depict spatial objects. On an underlying sampled surface, these dots indicate the geometric coordinates of a single point in X, Y, and Z. Many individual spatial measurements are combined into a dataset that can represent an entire region by point clouds.

3D processing software includes Cyclone, Scene, and Recap. Currently, both the software and hardware are made and developed by the same company, but they are restricted to processing. Technology and enablers do not have the requisite knowledge to develop a robust methodology. Initially, the main use of this technology was in robotics and healthcare, but it was later extended to various fields. One promising field in the engineering domain has been reverse engineering, where a 3D model is created from point clouds. The main goal of this imaging technology is to obtain the shape of the object.

The process can be broken down into distinct steps. First, measurements are done using a device that primarily uses light reflection. Based on the time of reflection, an array of points is created around the desired object, referred to as a point cloud. Next, the point clouds are loaded into specialized software, which stitches the point clouds to create an object's surface. Through various mathematical approximations, gaps in the point cloud (due to hardware limitations or imaging noise) can be bridged.

Point clouds are primarily stored in two formats: Binary and ASCII. The point clouds are typically registered with algorithms like Singular Value Decomposition (SVD), Principal Component Analysis (PCA), or Iterative Closest Point (ICP), all of which have been modified to suit user needs. These algorithms vary in accuracy and computational complexity, and their applications depend on the environment in which they are used.

The 3D point clouds can be baselined into a geometry manually and baselined and after that the real-time images can be used to compare deviations from the baseline geometry. The models created through these processes can be used for statistical analysis to evaluate the rate of change of deformation. This will greatly aid in determining the Remaining Life Assessment (RLA) of

the asset and in assessing Fitness for Service (FFS). One of the main objectives of this research is to use photogrammetry to achieve the work typically done by laser-based systems, but with lower hardware resolution and higher resolution (through approximation) via image enablement.

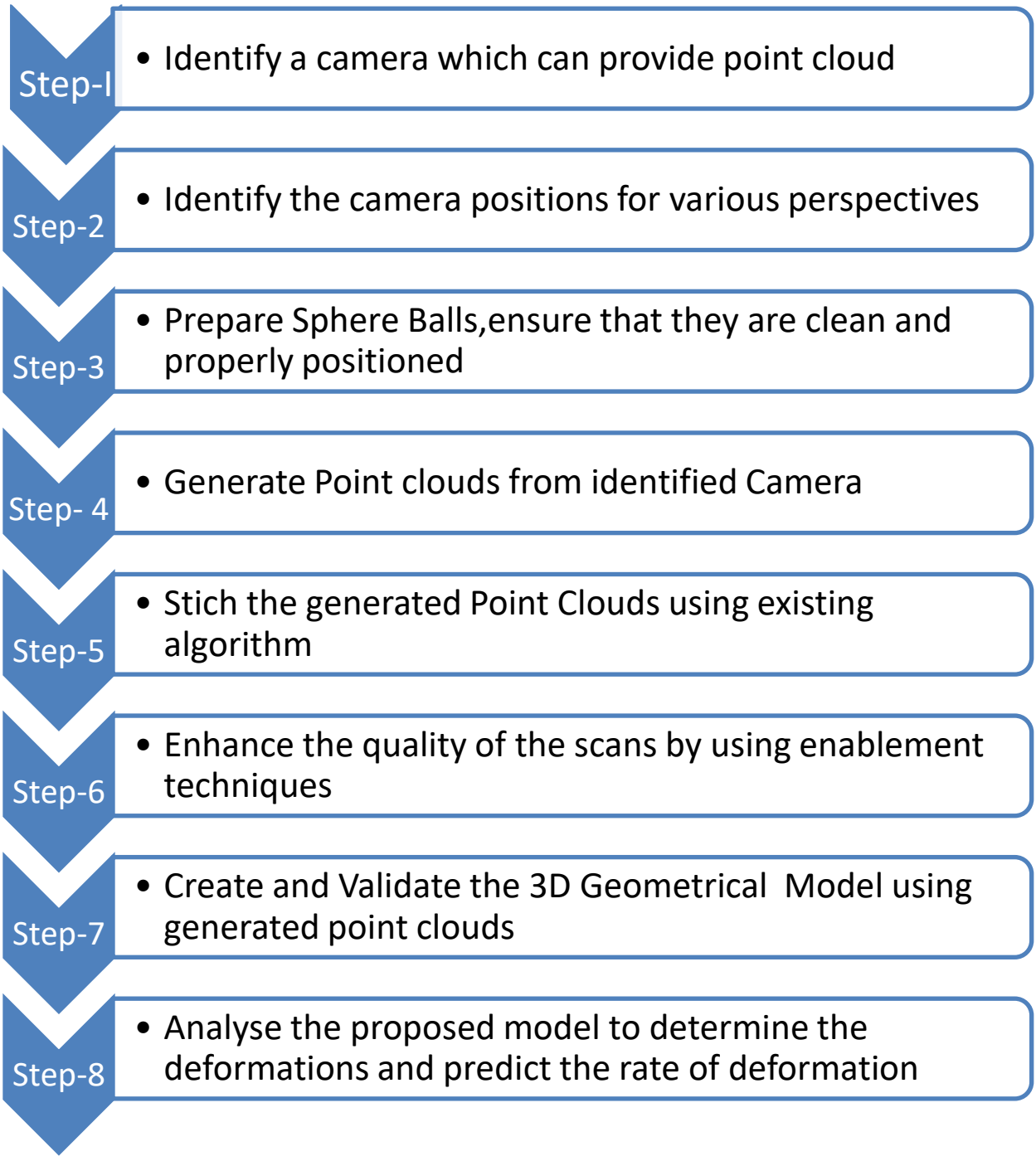
Step-I
• Identify a camera which can provide point cloud
Step-2
• Identify the camera positions for various perspectives
Step-3
• Prepare Sphere Balls,ensure that they are clean and properly positioned
Step- 4
• Generate Point clouds from identified Camera
Step-5
• Stich the generated Point Clouds using existing algorithm
Step-6
• Enhance the quality of the scans by using enablement techniques
Step-7
• Create and Validate the 3D Geometrical Model using generated point clouds
Step-8
• Analyse the proposed model to determine the deformations and predict the rate of deformation

Figure:1 Proposed Methodology (Source Self)

7. Expected Outcome of the Research

The expected outcome of the research will be a method which will allow us to get the point clouds from a robust low maintenance camera. The images in the camera can be stitched together using an algorithm and these images can be enhanced for extraction of better point clouds. The point clouds hence generated will be used to create a Geometrical model which in turn can be used for various computational analysis.

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SHORT SYNOPSIS

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by

Dhritiman Mukherjee

21/Ph.D/044

Under the supervision of

Dr. Parul Gandhi

Professor, School of Computer Applications

MANAV RACHNA
VIDYANTUL DARSHAN

Department of Computer Applications

School of Computer Applications

Manav Rachna International Institute of Research & Studies Sector-43, Surajkund–Delhi Road, Faridabad– 121004

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